USE OF TERRESTRIAL PHOTOGRAMMETRY FOR MONITORING AND MEASURING BANK EROSION

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ABSTRACT

This paper examines the use of terrestrial photogrammetry as a technique for measuring bank erosion in a rapidly changing fluvial environment. It has been recognized that there are a number of advantages when applying photogrammetric techniques to geomorphological situations. In this study the enhancement of spatial sampling combined with the ability to capture additional information, such as soil moisture, on film, is of particular importance in enabling the identification of specific processes involved in bank erosion as well as detailed volumetric analysis of losses.

Metric terrestrial photography was taken of the river bank on several dates, and data were abstracted by the use of analytical photogrammetry. This enabled the generation of digital terrain models from which morphological and volumetric changes could be assessed. © 1997 John Wiley & Sons, Ltd.

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INTRODUCTION

Traditionally, bank erosion has been monitored by intensive fieldwork involving the use of erosion pins or cross-profile surveying. These methods have several limitations: firstly, they involve interference with the bank face being measured; and secondly, the spatial resolution is limited to the points under investigation. Photogrammetry reduces spatial sampling problems and enables bank erosion to be monitored with minimal contact on the bank face itself. Although the method of terrestrial photogrammetry does involve surveying of ground control, the amount of fieldwork involved is less than that required by traditional methods of monitoring. It also has the great advantage that all data are archived and further information may be retrieved at a later date. The use of terrestrial photogrammetry in fluvial environments dates back to the 1970s (Painter *et al.*, 1974; Collins and Moon, 1979); however, these studies used analogue plotting machines, which were inflexible, causing constrictions on data interpretation and output. The analytical stereoplotters are far more flexible for setting up models and for data abstraction and analysis.

ANALYTICAL PHOTOGRAMMETRY

Differences between analogue and analytical photogrammetry

Photogrammetry is based on the principle that a three-dimensional, stereoscopic image may be obtained by using overlapping, displaced pairs of photographs. Provided that parameters of the camera and its relationship to the study surface are known, then the images can be orientated and scaled using control points, such that heights and height differences, as well as horizontal position, can be measured accurately on the images. The analogue solution achieves the orientation and scaling via a mechanical method, and as a result the physical properties of the analogue plotter can prove to be limiting in terms of the type and size of the photography used and the amount of adjustment that can be made. The analytical plotter follows the same basic principles except that it uses a mathematical solution. This allows greater flexibility in terms of application through the plotter's

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ability to handle different formats, scales of photography and a much greater range of distortion and obliqueness of the image. The analytical plotter used in this study was the Kern DSR-14; however, the majority of the points and procedures would be applicable to most analytical plotters.

The photographs

The diapositive is the optimum image format for use in an analytical plotter, but through the addition of an additional illumination system normal photographic prints can be used. Similarly, the image size can also vary from the typical 14 cm^2 frame through to 120 formats and even 35 mm transparencies, provided sufficient camera calibration information is known. The quality of the image is also dependent on the properties of the film and, therefore, care must be taken in choice of film type and exposure times. For terrestrial photogrammetry, slower, less sensitive films are preferable because of the smaller grain size within the emulsion which allows a greater resolution (Wolf, 1983), and an ISO of 100 or less is suggested. The longer exposure time required for films of this type is not a problem when the camera is mounted on a tripod and the target is stationary. Also, to enhance the depth of field characteristics of the image, it is necessary to use a small aperture size (or *f* setting); this will also reduce the potential amount of lens distortion. Each camera will have its own optimum *f* setting for best depth of field with the minimum amount of distortion, but this setting will generally be either *f*-16 or *f*-22. The taking of test shots is advised, especially in the case of terrestrial applications.

The orientations

Like the analogue solution, analytical photogrammetry utilizes three phases when setting up the model: these are the inner (or interior), relative and absolute (or exterior) orientations. These orientations reconstruct the bundle of rays which projected the object onto the negative. The reconstruction allows the creation of the object-model which is used for the measurements (Ghosh, 1988).

The inner orientation can be defined as the restoration of the internal geometry of the camera at the time of exposure in order to obtain a true stereoimage. For analytical photogrammetry, the fiducial coordinates and principal distances of the images are input into the computer via the selection of the correct camera calibration table. The stereopair is then placed on the photocarriers and the fiducial marks are digitized in order to create machine coordinates for them. The plotter will drive to the vicinity of the marks whereupon the operator will fine point them with the measuring or ‘floating’ mark. From this information a coordinate transformation is solved; residuals are then displayed so that the operator can either accept the measurements or remeasure. Corrections can also be made for lens distortion, atmospheric refraction and Earth curvature by inputting this additional information. The accepted inner orientation parameters are then stored (Wolf, 1983).

The relative orientation is the restoration of the same perspective conditions that existed at the instants of exposure of the two photographs in the stereopair. This is achieved by removing what is termed the y-parallax (Ghosh, 1988). The instrument drives to a minimum of six preselected positions where the y-parallax is removed. More than six measurements is recommended in order to generate a more parallax-free model. Again, points can be remeasured, and when the operator is satisfied with the residuals, the parameters are stored.

The final process of absolute orientation is carried out in order to bring the model to the desired scale and level it relative to a horizontal datum by using ground-surveyed control points. In order to accomplish this the ground coordinates of all the control points have to be entered into the computer. The operator then measures each of these points within the stereoscopic image. For this process a minimum of two plan points and three height points are required, but again more than this is recommended so that a least-squares solution can be made. The model is then scaled, shifted and rotated mathematically to obtain the best fit to this control. This process is analogous to that of performing an absolute orientation on an analogue machine solving for phi, omega and kappa. Again the operator can accept, add or remeasure any of these points until the residuals are satisfactory and the solution is stored.

The three orientation processes described above can be undertaken for each model in approximately 15 min, and once they have been carried out for the first time and saved, a model can be restored in less than 5 min. This is a vast improvement on the amount of time required to set up a model on an analogue plotter. Having set up the model, one can then instantly start to make measurements of the relative location of points on the image, and

their relative heights, by placing the measuring mark on the ground. These data are then recorded using the digital mapping software integrated with the analytical plotter as either individual points or as strings of points such as contours or boundaries.

Data capture

Data can be captured using a range of methods; for example, the Kern DSR-14 plotter can be used to produce very accurate planimetric maps displaying buildings and field boundaries etc. However, one of its most powerful uses is for the generation of height information for a surface in order to produce digital terrain models (DTMs). This applies equally when analytical photogrammetry is used with terrestrial photographs and it is in this context that the following is based.

The grid method. The integrated digital mapping software (in our case Kork) can overlay a hypothetical grid on top of the model. The plotter will then drive the floating mark to each intersection for the operator so that the height can be measured. This will create a grid of heights at a uniform density and can be performed by either working down the rows and along the columns, or randomly where the plotter drives between each intersection in a random pattern. The latter method has been shown to improve operator accuracy as there is no 'drag' effect between each measurement when change in the landscape is particularly subtle. Composite grids can reduce the amount of redundant data especially for areas of mixed relief. A fairly coarse grid can be used for the initial measurement of the whole model followed by denser grids over areas of more dramatic change in relief (Petrie, 1990).

The contouring method. This method requires the operator to fix the floating mark at a desired height by locking the z wheel (the height-measuring control) on the plotter. Contours are then digitized, at a user specified interval, by the operator tracing around the model whilst keeping the floating mark on the ground. The density of points created by the digitizing can be increased or decreased by the user stipulating the number of points to be dropped per unit distance travelled within the model. Additional individual points can be measured in between the contours to increase the density if so desired.

The random point method. Individual points are measured across the model in an evenly distributed manner; however, density can be increased for areas of rapid change in relief and breaks of slope. This is particularly useful for the geomorphologist as this method will produce a more realistic and accurate representation of the morphology when the data are interpolated for the production of a DTM (Petrie, 1990).

Revisiting specific points. A macro facility provided by the operating software of the plotter allows the data capture routine used on one stereomodel to be repeated identically for another. This is particularly useful when considering a time series of models over the same surface.

The choice of method selected for data capture, as in any sampling, depends on the purpose and analytical requirements.

Graphical display of data

The digital data abstracted using photogrammetry can be input into many different terrain modelling packages such as Surfer for Windows. This particular software interpolates a grid from the original x, y and z data exported from the analytical plotter. This interpolation can be carried out by a variety of methods (see Table I). The gridded data can be used to generate powerful visual representations of the surface, such as contour mapping, or one of the most powerful visualizations, the three-dimensional digital terrain model. The terrain modelling software, in addition to providing a good visual representation of the surface, also allows volumetric and planar area calculations to be carried out between models of the same area that were captured for different periods of time, a particularly useful function for the geomorphologist. For example, in this study the initial model of the river bank (derived from photography taken on 28 February 1995) forms the basis for the volumetric change analysis, enabling quantification of volumes of sediment entering the channel.

Table I. Interpolation methods. Source: Keckler (1995)

Interpolation method	Summary
Inverse distance	• Weighted average interpolator; weight of one data point diminishes with distance from the grid node. • Normally an exact interpolator; honours the data points when they coincide with a grid node; can add a smoothing parameter if desired. • Tends to create concentric rings around data points. • Fast for medium sized datasets.
Kriging	• Geostatistical gridding method; has proven to be popular. • Generates visually appealing contours that attempt to depict trends in the data. • Uses irregularly spaced data; good for random point photogrammetric method. • Can be an exact or smoothing interpolator. • User can define specific variogram model. • Can be slow for large data sets, but results are worth the wait.
Minimum curvature	• Popular in the Earth science. • Generates the smoothest possible surface while trying to honour each point. • Is not an exact interpolator, so not all points are honoured exactly. • Fast for most data sets.
Nearest neighbour	• Assigns the value of the nearest datum point to each grid node. • Useful when data are already on a grid, or for filling holes when data values are missing for a grid.
Polynomial regression	• Used to define large-scale trends and patterns within the data. • Not really an interpolator as does not attempt to predict unknown z values. • Very fast but detail lost within the resultant grid.
Radial basis functions	• Consist of a range of exact interpolators that attempt to honour the data points. • Multiquadratic is probably the best for a smooth surface that fits the data. • The results are similar to those produced by kriging.
Shepard's method	• Uses inverse distance weighted least-squares method. • Similar to inverse distance but local fit reduces concentric circle effect. • Can be an exact or smoothing interpolator.
Triangulation with linear interpolation	• Uses optimal Delauney triangulation. • Original data points are connected by lines to create triangles, produces a patchwork of triangle faces over the extent of the grid. • Is an exact interpolator. • Good for evenly distributed points; with large enough data sets breaks in slope can be preserved.

CASE STUDY

A study on the River Yarty in Devon, England attempts to identify the relative importance of bank erosion as a supply of sediment to the channel, as opposed to sediment supplied from the slopes and the bed itself. It will also provide information on the mechanisms and dynamics of that input. Although there is an abundance of bedload sediment upstream of the study reach, it is hypothesized that much of the bedload at the downstream end of the reach is derived locally from bank erosion. The aim is to quantify the inputs, storage and outputs of sediment and assess the budget and balance of sediment in the reach. In this case photogrammetry of the bank is being combined with conventional surveying of cross-sections to obtain the bed profiles (subaqueous) and with tracing experiments of sediment movement. There are three main layers to the eroding bank (see Figures 1 and 2). At the base there is a cobble layer then a gleyed layer beneath a deep silty layer. This paper examines the use of terrestrial photogrammetry as a technique for calculating volumetric changes along this 60 m eroding bank face.

METHOD

Preliminary fieldwork

Prior to making the first photographic run, it was necessary to visit the site and carry out a dummy run to test out the plan of action for future photographic shoots. This was particularly important in determining the type of film to use as the quality of the stereoimage is dependent on the film properties. It is therefore critical that the

Figure 1. Viewing of eroding bank face

Figure 2. Layers within bank

speed of film and exposure times are appropriate for the light conditions. The camera used for this study was a Pentax 645, with a custom-made réseau plate behind the lens with fiducial marks scribed onto it. This plate created fiducial marks on the image at the time of exposure, a necessary feature for the inner orientation described earlier.

Camera stations were set up along a 60 m baseline along the opposite side the river and parallel with the eroding bank. The stations were positioned to give a 60 per cent overlap between photographs. Stakes were inserted into the ground at the camera stations in order to aid relocation (with the use of a metal detector) for future photogrammetric visits.

The bank was targeted with small circular white discs, bearing a cross through the centre, in order to generate ground control. These were pinned randomly on the eroding bank, with minimal disruption. Within each stereoscopic pair it is necessary to have at least six common targets to generate ground control, but in case of problems of ‘line-of-sight’ to the targets (owing to a fallen tree and the irregular nature of the bank face) extra targets were placed on the face in order to guarantee sufficient control. These targets were then surveyed in

Figure 3. Ranging poles and targets are used to generate control within the images

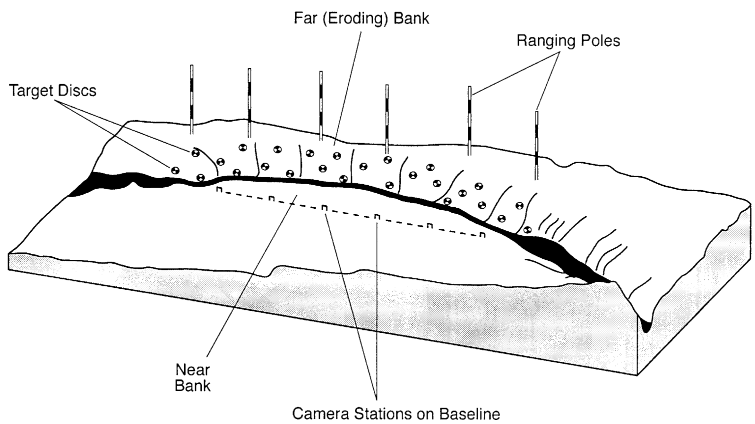

Figure 4. Diagram of the site

order to generate coordinates for each of the discs for the process of absolute orientation. This was carried out by placing the prism in front of each disc.

Ranging poles were positioned in front of each of the camera stations on the opposite bank above the eroding bank face; these acted as an additional control in the photographs for the process of relative orientation (see Figures 3 and 4).

On returning to the laboratory, the photographs were processed and viewed through the stereoplotter, as a result of which a few improvements to the method were made.

Revised methodology

Firstly, it was decided that due to the grainy quality of the image produced during the pilot run, using a 200 ISO film, a slower 100 ISO film would be used.

Secondly, the discs used as targets in the pilot study bore a black cross, which was hard to detect on the photographs; it was therefore decided that shading in two diagonally opposite quadrants of the discs would aid detection.

Thirdly, the ground control survey could be improved by omitting the use of the prism, which caused problems as a result of incorrect positioning due to the bank morphology. Instead, measuring the bearings and elevations of the centre of each disc from each end of the baseline would be used. It was decided that numbering the discs would avoid omitting data by skipping discs at the surveying stage. The intersections of the bearings could then be calculated geometrically at a later stage, back in the laboratory.

Fourthly, it was evident after the initial model was put into the DSR-14 analytical plotter that the tilt of the camera made measurements unnecessarily difficult. To compensate in the future, it was decided that having the camera as low to the ground as possible, and thus as level as possible in all planes, would make the photogrammetrical measurement simpler. However, as was stated earlier, the DSR-14 can compensate for very tilted photographs through its analytical solution, and so if no other solution had been possible in this case the tilted models could have been used. Four more photogrammetric runs have since been carried out, three of which produced photographs of a high quality, enabling analysis. Figure 4 shows an annotated diagram of the site.

Photogrammetrical data capture

Having carried out the orientations for each model and accepted the residuals for each of the stages (see Table II for an example typical of the residuals accepted for the absolute orientation of a model), data capture via the integrated Kork software was now possible. On considering the many available choices of data capture it was decided that the random point method would be the most appropriate. By using this method, extra points could be measured for areas of sharp change in relief, while the rest of the bank face would be measured in an evenly distributed manner. This data capture method, when coupled with the kriging interpolation routine, was considered to be the best way for modelling the morphology of the bank, especially when one considers how the kriging attempts to honour the data set according to the trends within the data. Each stereopair was measured by this process, with the data from each new pair being merged with the last. As a result, a total of 7483 data points were recorded for the whole of the bank face for the first photographic run. This data set provides the baseline against which the more recent photographic runs can be compared.

Owing to the long, thin nature of the data set generated, it proved to be very difficult to produce a graphic visualization of the entire bank face in one complete strip. Hence, it was decided that cropped sections of the bank face would give an improved result. However, for the volumetric calculations, the bank face would be treated as one as there is no need for an aesthetically pleasing visual output. Figure 5 shows a DTM of one of the cropped sections of the bank produced by this method of terrestrial photogrammetry.

Table II. Typical residuals for a model

Model No. 28282827		Ground coordinates			Residuals		
	Point name	E	N	H	DE	DN	DH
1	58	0·68	9·49	31·63	0·00	–0·00	0·03
2	46	15·49	9·82	27·14	0·01	0·01	0·01
3	47	14·49	9·60	26·91	–0·00	–0·00	–0·01
4	49	10·65	9·10	28·35	–0·01	–0·01	0·02
5	53	5·88	9·60	29·73	0·00	0·00	–0·04
6	55	3·49	9·19	30·30	–0·00	–0·00	–0·04
7	56	2·05	9·66	30·81	0·01	0·01	0·02

Standard plan deviation = 0·025; standard height deviation = 0·038

From the residuals in Table II it can be seen that the model was accurate to approximately ±3 cm at the worst case, with the operator's measuring accuracy from this scale of photography of approximately ±0·5 cm, again at the worst case. These figures could be improved with more accurate ground control, and this has been achieved for later models with the use of a Leica 300 series GPS, which was used to set up a very accurate baseline. However, it is important to stress that it is the relative volumetric changes between runs of photograph that are of interest; a certain amount of error is inevitable with further generalization occurring through the interpolation process. Nevertheless, the spatial resolution is still far higher than that which could be achieved with other

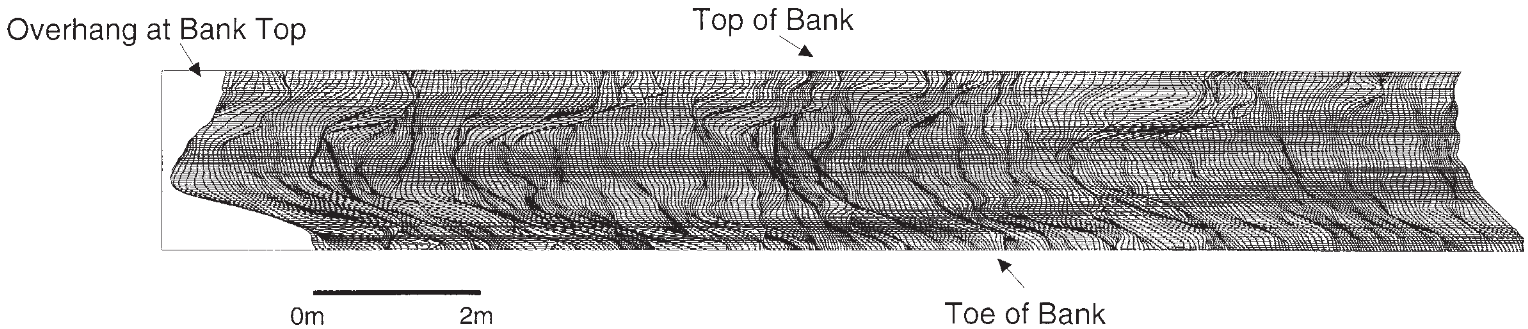

Figure 5. Digital terrain model photogrammetrically derived for a section of the river bank; photos taken 28 February 1995

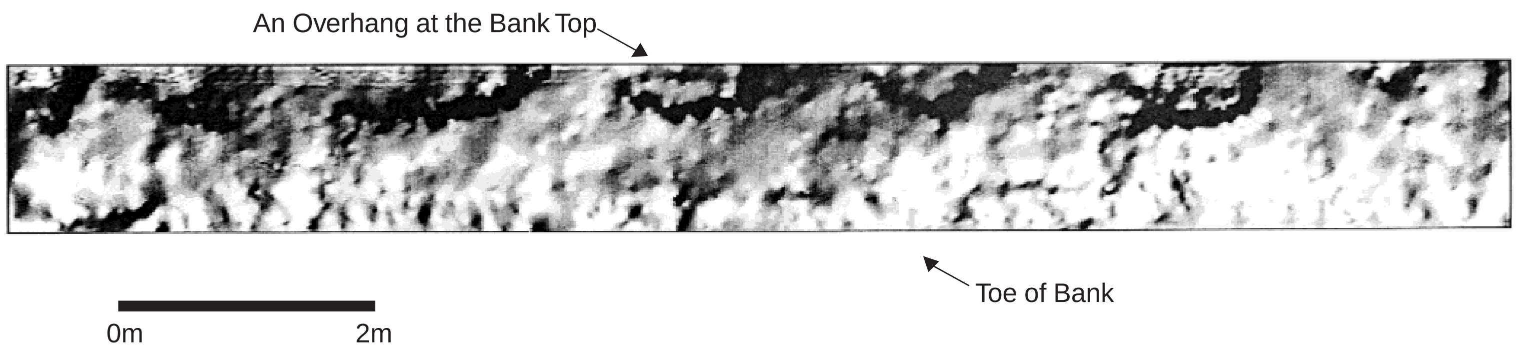

Figure 6. Shaded relief map for the same section displayed in Figure 5. NB This grid has been smoothed; note the dimpled effect of the smoothing around the data points, caused by the interpolation still trying to honour the data points. Care must be taken when smoothing grids

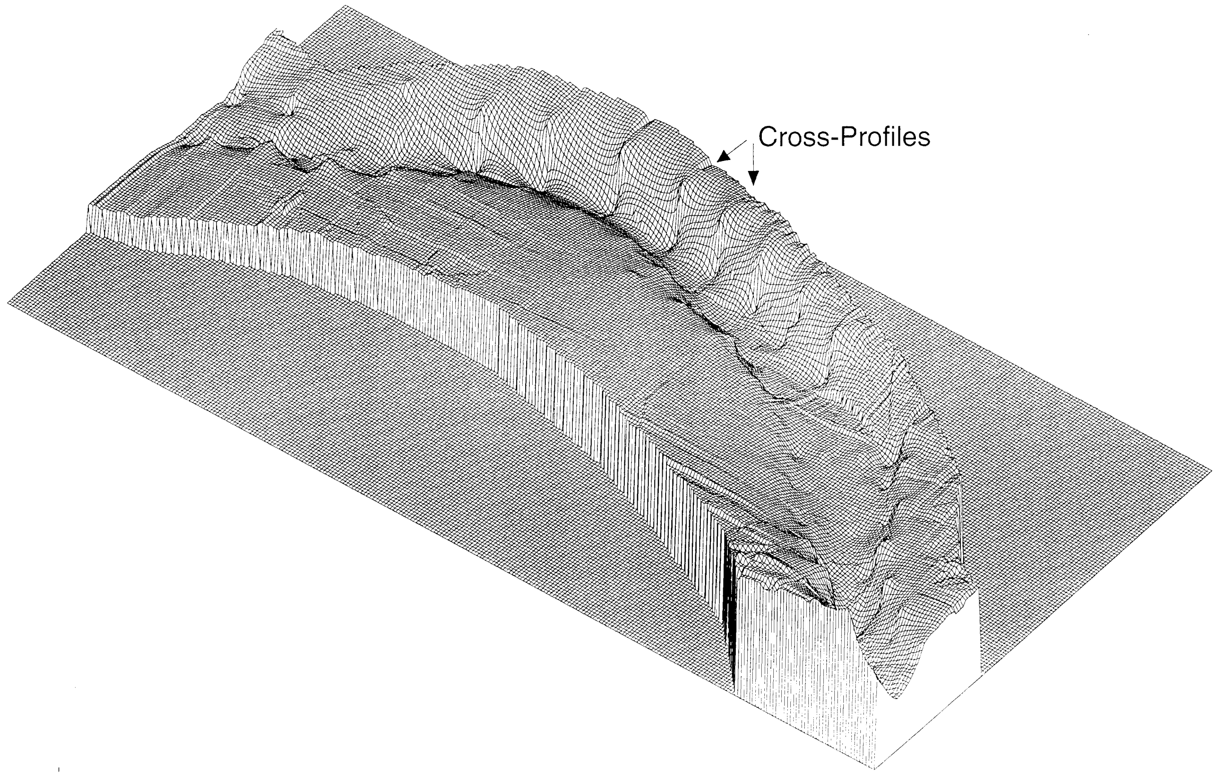

Figure 7. Digital terrain model produced from cross-profile data for the 60 m reach of the River Yarty, Devon. NB The DTM highlights the necessity for a higher density of data points for detailed terrain modelling

techniques previously used. Figures 5 and 6 show DTMs of the bank produced by the method of terrestrial photogrammetry.

DISCUSSION

The method of analytical photogrammetry enables accurate, detailed digital terrain models to be produced. The spatial resolution is far greater than that achieved by erosion pin monitoring and cross-profiling.

Figure 7 shows a DTM produced from cross-profile data. These cross-profiles are taken at 10 m intervals down the reach. As can be seen from the DTM, there is relatively detailed information across the river at each of these profiles; however, the sections in between are inferred from the two adjacent profiles, which are 10 m apart. This is a result of using the kriging interpolation method, which is an exacting method and hence tries to honour all of the data points. The DTM highlights the necessity for a higher density of data points for detailed terrain modelling. This method of monitoring will pick up large changes that occur; however, detailed changes such as volumetric contributions from the bank, which are spatially variable, cannot be picked up. 'The technique of repeated cross-profiling is not particularly sensitive to erosion that is highly localized in space and/or sporadic in time' (Lawler, 1993, p. 796). The data provided by photogrammetry alone produce detailed DTMs of the bank (Figure 5) but do not given information on volumetric changes within the reach.

In this particular study the part of the bank which is of most interest (the coarse fraction, generating bedload) is partially subaqueous, hence it is necessary to back up the use of photogrammetry with traditional monitoring such as cross-profile surveying.

The technique is potentially very useful for looking at mechanisms and location of bank failure. From photogrammetric analysis one will be able to determine volumes accurately as well as calculating within which sections of the bank losses have occurred. Information can thus also be generated on the size, position and mode of failure of blocks. Additional information captured on the image, such as soil moisture conditions between events, can also be used to help establish failure mechanisms. The method also allows detailed temporal monitoring, which is important in a rapidly changing environment. Photographic data can be taken after events, thus generating losses between events; however, it is not possible to establish information within events, such as can be derived from photo-electronic erosion pins (Lawler, 1989). The advantage of data being captured on film is that the information is archived and hence the labour intensive part of the technique – processing the data – can be carried out at a later stage; this is beneficial if constant monitoring needs to be maintained at the field site during the winter. The advantages of the techniques are clear to see from the detail on the digital terrain model, but there are a number of considerations that need to be taken into account when using photogrammetry to monitor bank erosion.

Although fieldwork time is greatly reduced compared with traditional techniques, one is still required to survey ground control. In the case study above, this involved measuring 50 targets from each end of the baseline.

A major consideration is that data capture is the most time-consuming aspect of analytical photogrammetry. A balance needs to be established between the number of points abstracted and the level of accuracy required for the interpolated surface. In the case outlined above, 7483 points were abstracted over the 60 m bank face. The accuracy is dependent not so much upon the precision of a point measurement but on the fact that the technique enables a spatial coverage far in excess of that achieved by traditional, point-specific methods, hence it is the sampling of points that is important as much as the individual locational measurements.

One also needs to consider the location of any potential photogrammetric site. Firstly, for the above technique, one needs to be able to access the bank in order to position control points on the eroding face. Secondly, obstacles between the baseline and bank face, such as vegetation, can greatly reduce the applicability of this method by obscuring the image. Thirdly, the baseline needs to be positioned so that one can capture the entire eroding bank face; if one has a narrow river with steep banks on both sides, there may be a problem that the nearside bank obscures the view of the opposite eroding bank face.

CONCLUSION

Where ideal conditions exist, such that photography of the bank is not obstructed and the bank is accessible, terrestrial photogrammetry is an advantageous method for monitoring bank erosion. The technique of using cross-profile data to provide generalized geomorphic characteristics of the reach, combined with photogrammetric data at sites where detailed geomorphic change is of importance, provides an accurate method of monitoring geomorphic change. This is particularly beneficial in a rapidly changing environment.

The suitability of the technique is obviously dependent upon the specific nature of the study and the level of accuracy required. For the purpose of sediment budget studies, requiring detailed volumetric calculations of sediment entering a reach from a bank, although labour-intensive, terrestrial photogrammetry is a very accurate technique.

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